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Narrow coronal holes in *Yohkoh* soft X-ray images and the slow solar wind

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Abstract. Soft X-ray images of the solar corona sometimes show narrow dark features not obviously present in HE I 10830Å images. We term these "narrow coronal holes" (NCHs). A prototype for this type of structure crossed solar central meridian on October 29, 2001. Standard source-surface models showed open magnetic field lines in this feature, tending to confirm its identification as a coronal hole. The magnetic field in this example is relatively strong (above 100 G in the low-resolution Kitt Peak magnetograms), and the boundaries of the open-field domain fall within the unipolar area as expected. We have surveyed the *Yohkoh* SXT data for other examples of this phenomenon, and have found several candidates. From observations of the associated solar wind, and from modeling, we find these regions to be sources of slow solar wind.

INTRODUCTION

The solar wind arguably consists of two kinds of long-lived flows, the slow and fast solar winds. The fast wind originates in coronal holes (CHs), but the source(s) of the slow wind have been controversial. Perhaps the first idea was that the slow solar wind originates on open field lines within CHs but near the boundaries where the magnetic flux tube expansion is largest ([1], [2], [3]) This idea is complicated by the suggestion that at solar maximum the slow wind can apparently ([4], [5]) originate in small isolated CHs whose field lines may be strongly diverging, and by the observed association of active regions and solar-wind flow ([6], [7]). The appearance of white-light blobs in LASCO observations suggested to Wang et al. [8] that the slowest and densest solar wind originates in helmet-streamer loops but with a major component still originating from inside CHs near the boundaries.

The boundaries between the slow and fast solar winds during the first southern polar pass of the *Ulysses* spacecraft were distinguished by relatively sharp spatial boundaries of the values of O^{+7}/O^{+6}, Mg/O, and Fe/O in the SWICS instrument [10]. The ratio O^{+7}/O^{+6} in particular reflected freeze-in temperatures of either ~1.6 MK in slow solar wind or ~1.3 MK in fast solar wind. The corresponding solar wind speed profiles at the boundaries were much more gradual, having been washed out by stream-stream dynamics. Longer time averages of the *Ulysses* O^{+7}/O^{+6} observations showed a simple low-temperature freezing-in process for the fast solar wind but a more complicated range of high charge states for the slow wind [11]. A more structured slow solar wind was observed in the ecliptic plane with the *ACE* SWICS O^{+7}/O^{+6} observations [12].

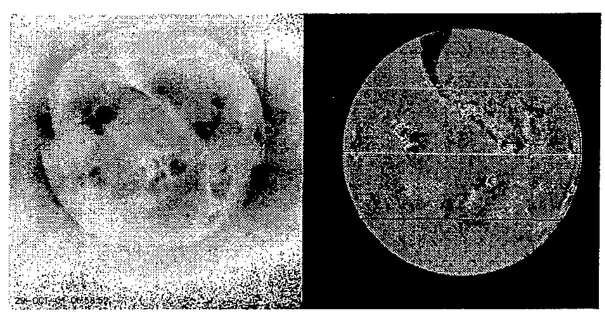

FIGURE 1. Representative narrow coronal hole (NCH) observed by *Yohkoh*, 29 October 2001. The north polar hole can be seen to extend to the southwest (lower right) into a strong-field region towards NOAA region 9678 (N07, W21), as shown in the rough overlay over the KPNO magnetogram on the right.

If the Earth traverses solar wind originating in an NCH, we can examine both the speed and O^{+7}/O^{+6} profiles at 1 AU to determine whether or how much of the solar wind from the NCH appears to be fast wind. Such a traversal would intersect solar wind flowing from both the NCH boundaries and the middle of the NCH.

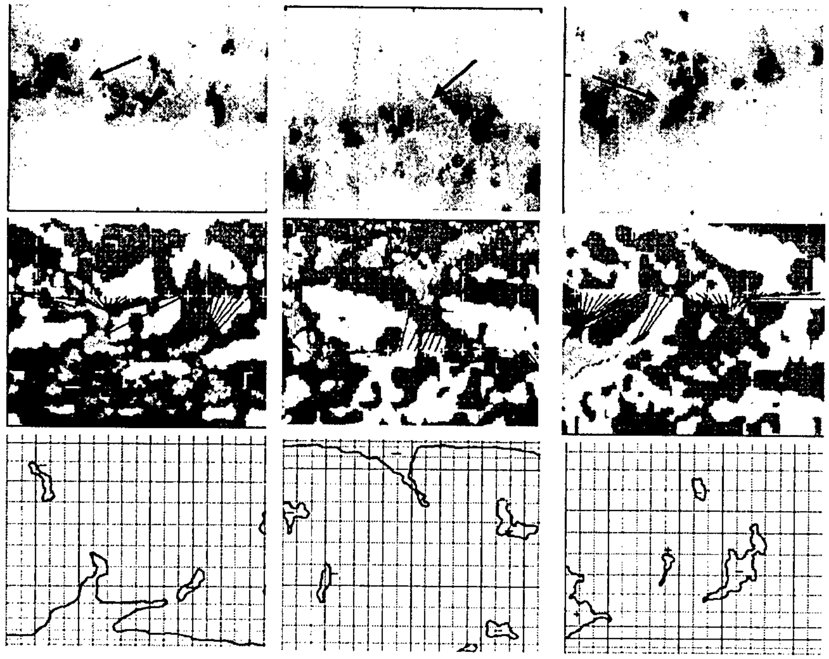

FIGURE 2. Synoptic maps (top, *Yohkoh* soft X-rays; middle, model magnetic field; and bottom, HE I 10830Å CH boundary map) for each of the three NCH episodes studied (left, CR 1851, the "YCH1" of [9]; middle, CR 1982; right, CR 1983). The arrows in the X-ray images point to the NCHs discussed in this paper.

The lack of any signature of fast wind could suggest that in some cases an NCH could be the source of only slow wind, contrary to the concept of CHs as sources of fast wind, at least in their centers.

The *Yohkoh* images from the Soft X-ray Telescope (SXT) give clear views of coronal holes of all sorts. For the purposes of this paper, we use the term "coronal hole" in the sense of "open field region" and assume that the darkest regions of a soft X-ray image during active periods can be identified with open fields (note that Figure 2 shows negative images, such that the CHs are lighter in color). In particular the SXT data often show the existence of NCHs as sharply-defined narrow features especially clearly seen near disk center. We examine the relationship between these narrow CHs and the source of the slow solar wind, which may depend upon rapidity of field-line expansion in the lower corona [13]. This work continues a series of studies using the *Yohkoh* SXT data to characterize CH boundaries in the lower corona ([14], [9]).

DATA ANALYSIS

We have selected three prominent cases of NCHs in the *Yohkoh* SXT data, each of which is a low-latitude extension of a polar CH. The approximate central meridian passage dates are: 28 January 1992 (CR 1851); 29 October 2001 (CR 1982, also shown in Figure 1); and 6 December 2001 (CR 1983). In Figure 2 we show synoptic X-ray, calculated coronal magnetic field, and HE I 10830Å CH boundary maps. Each image was cropped at 45° latitude in the hemisphere opposite the NCH and to a longitude range of 180°. Note that the top two images are linear in latitude, while the He image is linear in cosine latitude. The color coding of the magnetic field maps indicates the magnetic expansion factors of the open field regions, and each NCH was found to be a field region open at the 2.5 $R_\odot$ source surface with large (shown as green or blue) expansion factors, although the agreement of the boundaries is not exact. The agreement between the X-ray and coronal field maps supports the interpretation of the X-ray NCHs as true open-field CHs. On the other hand, the He CH boundaries omit significant regions of the NCHs, as well as showing other large disagreements with both the X-ray and coronal magnetic field open areas. This suggests that at least in NCHs the He images may fail to indicate the presence of open field regions.

The lines extending from the + signs in the middle panels of Figure 2 show the calculated source regions of the solar wind at Earth for each date. In each case we find that the NCH was a solar wind source. Since the general direction of the NCHs was north-south, the Earth

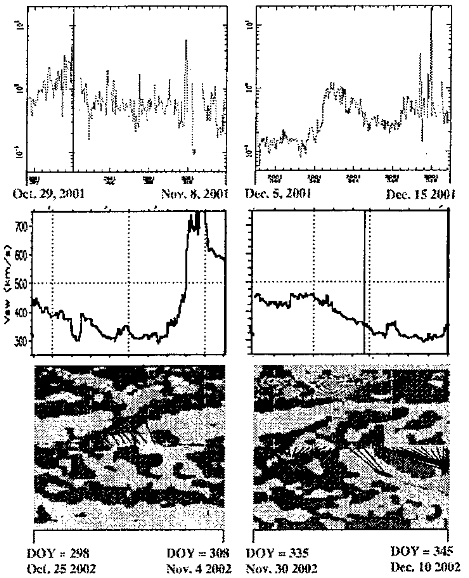

FIGURE 3. SW speed (middle panels) and O^{+7}/O^{+6} abundance ratios (upper panels) for the two most recent of the NCH examples. The panels on the left show the NCH of October, 2001, as imaged directly in Figure 1. The right column shows the NCH of December 2001. The lower panels show source-surface modeling; note that these images are reversed in time to match the SW data.

traversed the NCH boundaries and central regions. For the two most recent events of the study we can examine the corresponding speed and O^{+7}/O^{+6} profiles measured by the SWICS instrument [15] on the ACE satellite. These are shown in Figure 3 with the approximate times of the calculated passages of the solar wind from the NCHs. In the October 2001 period the O^{+7}/O^{+6} ratio is about 0.5 and in the December 2001 period about 0.8. These values are generally in the range expected for slow solar wind [12]. In addition, the solar wind flow is about 350 km/s and declining through both periods. Note that shocks were tentatively identified in the ACE data at 1300 UT on 31 October and at 0155 UT on 5 November, before and after the NCH solar wind in the October period. In addition, two shocks were identified at 2210 UT on 6 December and at 2300 UT on 11 December, again before and after the period of the NCH solar wind flow in the December period. These transient features do not appear to compromise the general association of the slow wind flows with the NCHs.

NARROW CORONAL HOLES

The initial motivation for this paper was the recognition that many of the small CH observed by *Yohkoh* SXT at low latitudes were in fact quite elongated. As Figure 1 illustrates (beware the negative representation), the apparent darkness of these features resembles that of larger-scale CHs. However the SXT data cannot easily be used to determine the physical parameters because of dynamic-range limitations, so the identification of these dark regions with "true" CH, defined as open-field regions, must remain an assumption.

In all respects that we have studied, these NCHs resemble ordinary CHs. In particular they do not exhibit obvious evidence for magnetic reconnection at their boundaries in the form of unusual heating or motions [9]. The NCH pattern is prominent even at SXT resolution (typically using 5″ pixels), and we believe that more systematic and detailed study at higher resolution may be fruitful as discussed below. The He I signature has limited resolution because of its excitation by coronal EUV emissions, which illuminate relatively wide areas of the chromosphere. As pointed out, studies using He I 10830Å may have systematically ignored these regions, which may contain relatively large magnetic fluxes (see Figure 1) [16]. The NCHs frequently extend into active regions, where 10830Å observations become confused, and we identify such cases with the open fields of active regions noted by Levine [17].

CONCLUSIONS

We have found NCHs to be sources of slow solar wind originating on open field lines. These may have escaped detection by He I 10830Å imaging. The source-surface models of these regions show large expansion factors, consistent with the Wang-Sheeley explanation [13], but do not implicate streamers directly. If reconnection takes place freely at the boundaries of these NCHs, and if their boundaries do map to the streamer locations, our results would be consistent with the idea of associating some of the slow wind with streamers. Thus far searches in the X-ray observations [9] have not shown evidence for reconnection in the form of heating or sudden motions, but more definitive data analyses could be carried out. The immediate problem to resolve is the apparent association of slow wind with open field lines (our result) and the earlier indications, from stream properties and from the "streamer blob" assocation [8], that closed field lines play an important role in the formation of the slow wind.

NCHs may escape detection via the standard He I 10830Å observations, although the source-surface models for coronal fields may reveal them. Such features may

have smaller expansion factors in the low corona, since they are long and thin – intuitively, the one-dimensional expansion from an NCH might not be so rapid as a two-dimensional one from a more symmetric CH. On the Wang-Sheeley hypothesis, this would suggest a weaker slow-wind flow pattern. However the NCHs may occur in strong-field regions (for example, the one shown in Figure 1), which would be consistent with larger amounts of solar-wind flow originating there. We do find from source-surface model calculations that the NCHs correspond to relatively large expansion factors. This preliminary look at the NCHs therefore suggests the need for a fuller survey that could confirm or deny the NCH/slow-wind relationship, and illuminate the role played by the expansion factor in these CHs.

In a recent work Neugebauer et al. [7] have confirmed the presence of open field lines in active regions (ARs). What we term NCHs may have even higher O^{+7}/O^{+6} ratios than the ones they cite for ARs, and for similarly active periods. Our NCHs often penetrate too close to active regions for good fidelity in the HE I signature, and we plan to study a more extensive sample NCHs to clarify their relationship to these AR sources.

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